Field-of-view Characterization of the Aura Microwave Limb Sounder using Lunar Surface Radiation

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This work was carried out at the Jet Propulsion Laboratory, California Institue of Technology, under a contract with the National Aeronautics and Space Administration.

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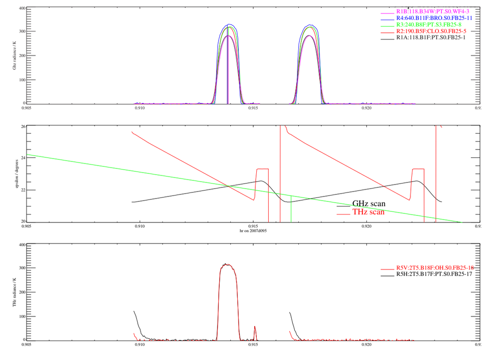
MLS antenna calibration refinement in-flight

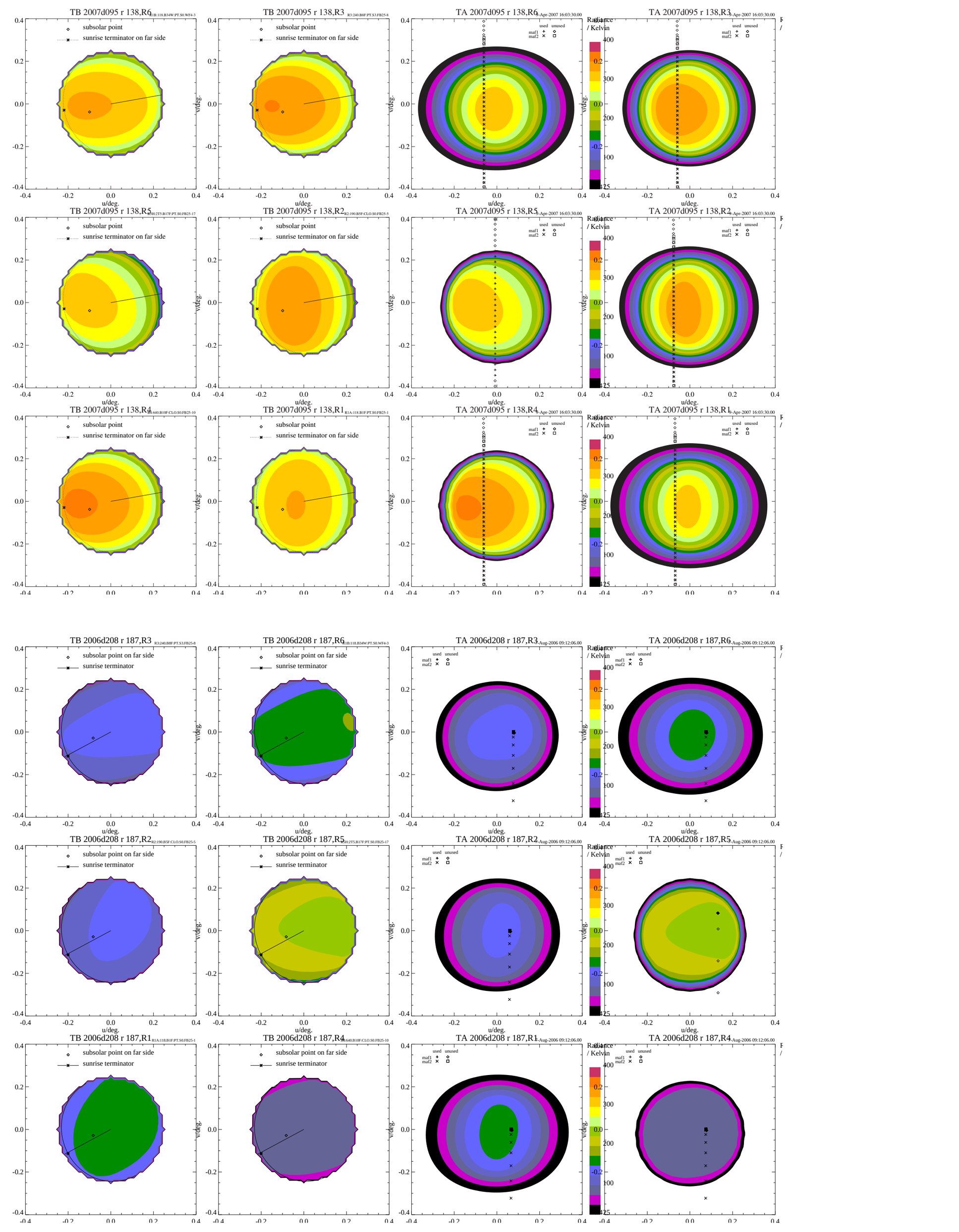
- In MLS' 1st 3 years of operation we used some of the bimonthly opportunities to scan FOVs across the Moon: 4 near full Moon (Lunar $\Phi = +26°$); 2 near new Moon ($\Phi = -157°$); Both GHz and THz scans were re-programmed for these *Moon Scans*. Calibrations have continued to the present as annual *Moon Tracks*, described below
- A Radiance–scan analysis model was updated from UARS MLS.
  - Steve Keihm supplied $\mathbf{T_B}$ maps from his extension of the lunar emission model [Keihm,*Icarus*, 1984] to Aura MLS frequencies.
  - We analyze MLS radiances as follows [Jarnot,1996; Cofield,2005]:
    1. Transform boresights to a $\mathbf{u}, \mathbf{v}$ coordinate system centered on the lunar disk. This makes software toolkit calls like those of Level 1 (L1) software.
    2. Resolve directional radiances for the $\mathbf{T_B}$ distribution along MLS polarizations. Smear radiance maps using measured FOV patterns (smearing due to integration time is much less significant than for UMLS).
    3. Using the gradient of these maps at $\mathbf{N}$ minor frame (MIF) Moon views, solve a $3\times\mathbf{N}$ linear system for 2 pointing offsets $\mathbf{du}, \mathbf{dv}$ and a model scale factor (Gain) $\mathbf{A_0}$. Re-evaluate gradient at the new pointing and iterate solution. Pointing typically converges within 4–6 iterations; $\mathbf{A_0}$ accounts for both model errors and FOV pattern uncertainty, and ranges from 0.9 to 1.1, as for UMLS.
  - Current analysis confirms the pre-launch values of pointing offsets; however the Aura MLS scan geometry limits our ability to establish pointing within 0.0003° (16 m at the limb—1 order of magnitude better than ground calibration), as was done in UMLS validation. Timed Aura Yaw maneuvers can circumvent this limitation.

Full- and New-Moon scan results

GHz radiance, Moon and encoder angles, and THz radiances in 2 major frames (MAFs) on 2007 d095. THz signature in MAF 28 is not shown.

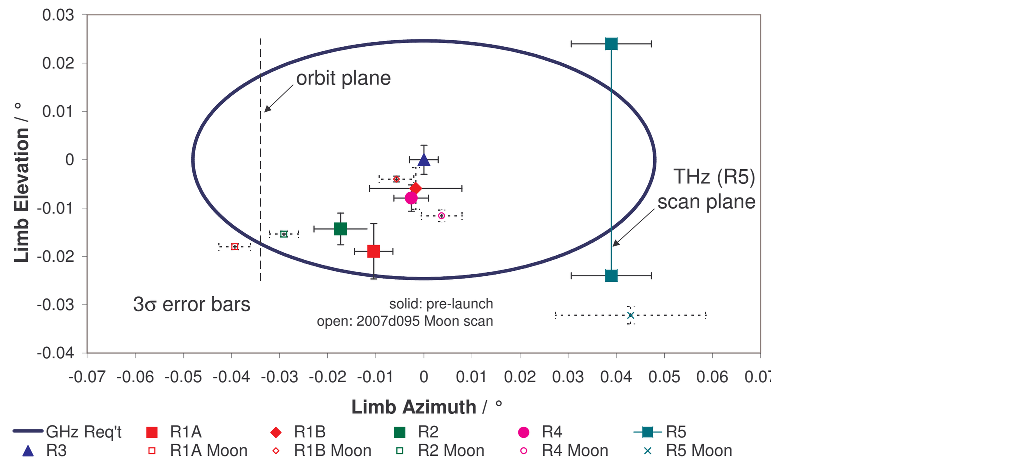


Below: Full(top) and New(bottom) Moon radiance maps: Polarized model brightness ($\mathbf{T_A}$, Left) and convolved radiances with MLS footprint ($\mathbf{T_A}$, Right)

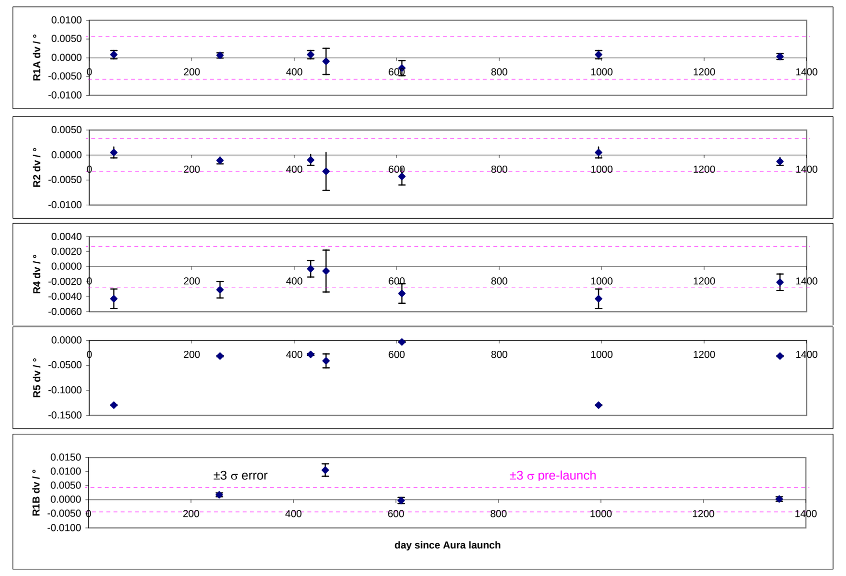


Pointing retrieval; Pooling multiple days

Pointing offsets from R3 (dFOV): requirement, pre-launch and 2007 measurement.



- Degeneracy of retrieved Moon model gain and horizontal pointing, due to Aura scan in orbit plane
- Vertical pointing agrees with pre-launch data.



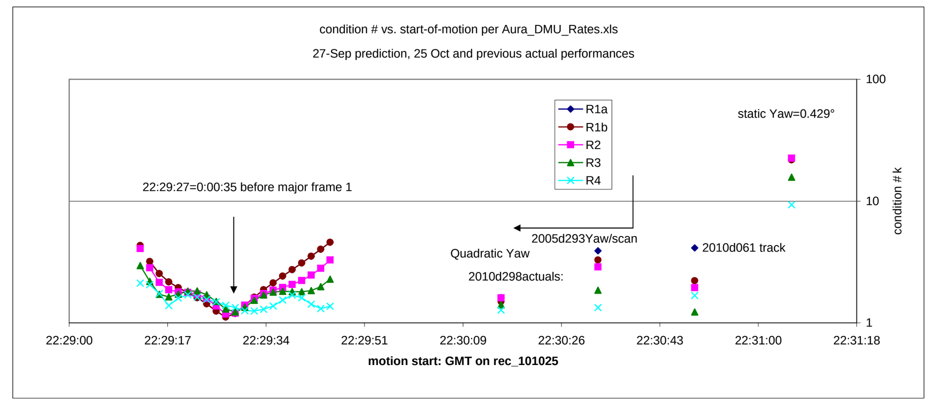
Vertical dFOV w.r.t. B8LF minus pre-launch values: unpooled full Moon scans

- Without pooling of days, each Moon Scan analysis involves solution of six $3\times\mathbf{M}$ regressions, with $\mathbf{M}$ the number of MIFs observed. *I.e.* $\mathbf{6N}$ normal equation $\mathbf{3}\times\mathbf{3}$ systems for $\mathbf{N}$ days.
- With pooling and reformulation so that only the reference (R3) pointing (not all 6) varies with days, the problem has a single $\mathbf{(6+10)+2N}$ rank system. The method was developed for UARS MLS Moon pointing retrievals
- The result for 2004–2006 Moon scans was a pointing set which matched the pre-launch values, with $\mathbf{3\sigma}$ errors reduced from 0.003°(pre-launch) to 0.0015°(this method)

Yawed Moon Scans

- in 2005 and 2010, Aura performed a Yaw maneuver synchronized with the MLS Moon scan

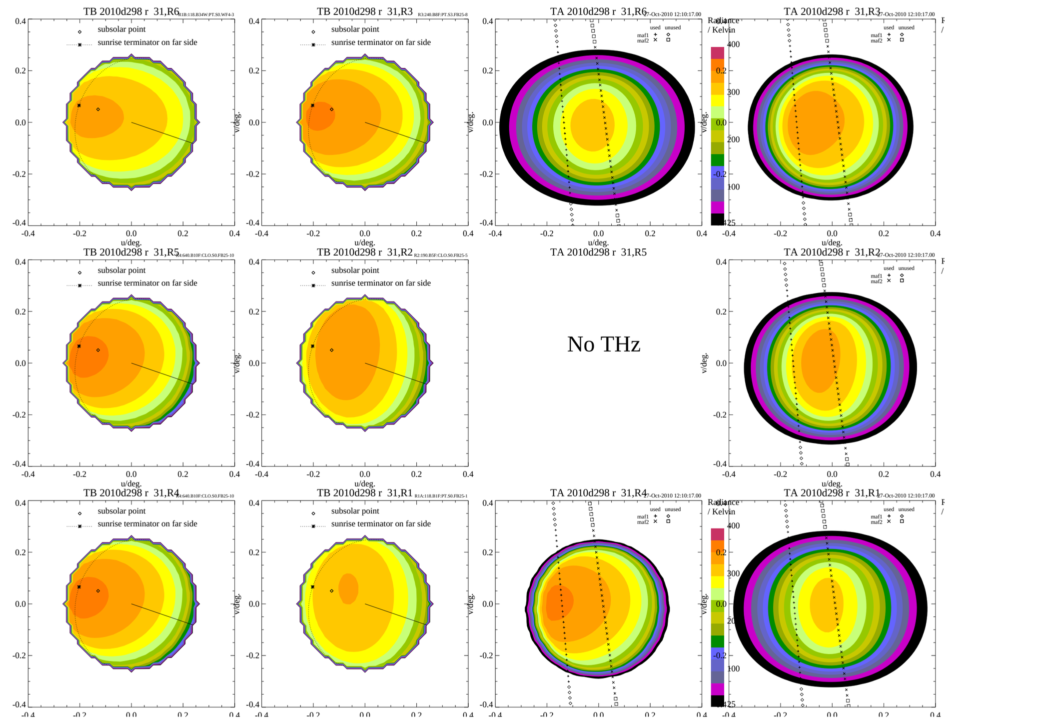
  program, to improve accuracy of retrieved relative pointing between GHz radiometer bands
  - We chose the closest day-of-year to give the same inclination of Moon equator with the MLS scan plane and to match MLS' solar heat load, in order to isolate secular from seasonal and orbit-dependent changes in pointing.
  - A 10 second lag between predicted and actual Yaw angles compromised the 2005 improvement in retrieval.
- For planning, Goddard developed an empirical Yaw profile from $\sim \mathbf{20}$ Yaw maneuvers (mostly DMUs) since launch. All these confirmed the 10 second lag. We tolerated a further lag of 0.8 seconds between these on-board data and the definitive attitude record, partly because the Aura Yaw can be commanded only on whole second intervals.
- Results: the timing error was eliminated and the retrieval improved accordingly.
  - There is no difference between pre-launch, 2005d293 and 2010d298 radiometer offsets within 3σ error bars.
  - The model scaling factor, retrieved along with pointing angles, shows a frequency dependence which suggests the arrangement and losses of the optical multiplexer elements. We studied this effect when pooling this scan with other years' data to reduce error bars below the levels of the pre-launch calibration.



- Matrix *condition number* quantifies how nearly singular is the retrieval of 2 pointing angles and model/antenna Gain.
  - We chose Yaw start time to minimize condition number, esp. in R1-2
  - For best condition number, Yaw separates footprints to straddle bright spot on Moon.
- 10 second lag in previous (2005) attempt degraded condition numbers to values comparable to more recent Moon tracking (see below).

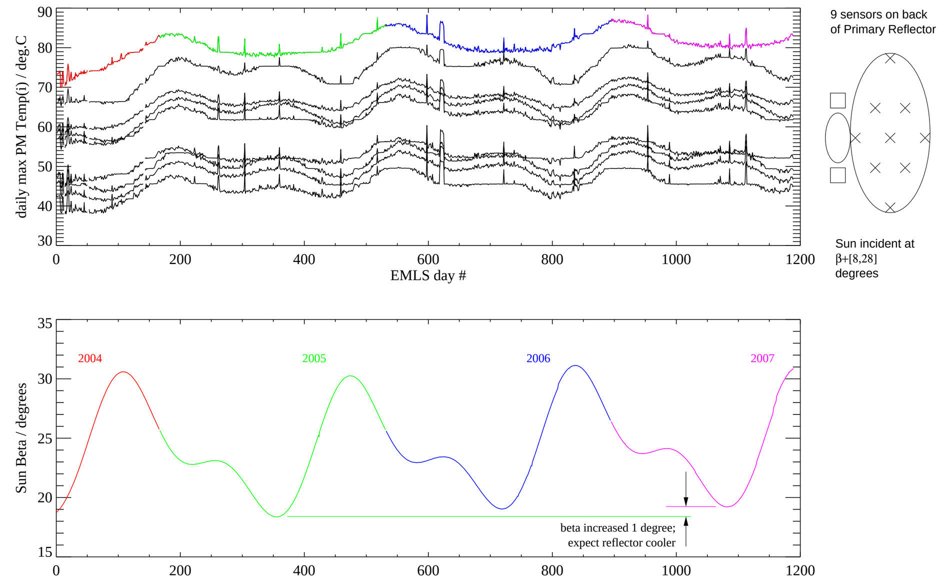
Yawed Moon Scan, cont.

Improved timing in the 2010 scan gave close-to-optimal condition numbers (each $<\mathbf{1.7}$).

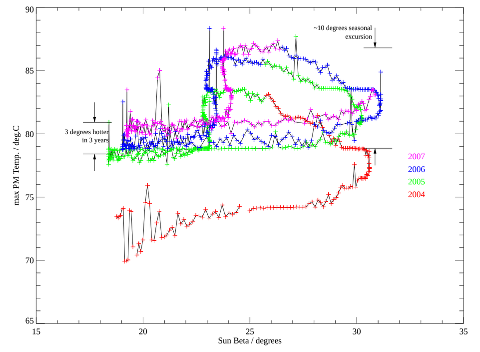


Evidence of Antenna Transmission changes in MLS

Periodic and secular variations in Reflector Temperature are tracked in the engineering assessment of MLS antenna performance–particularly for the Vacuum Deposited Aluminum (VDA) on the composite Primary Reflector.



In 1st 3+ years, both maximum reflector temperature and minimum Sun β increased—contrary to intuition.



Flat portion ($\partial T/\partial\beta \sim 0$), Jul–Nov agrees with dependence on day-of-year (not β), found in developing Level 1B (L1B) version 2.

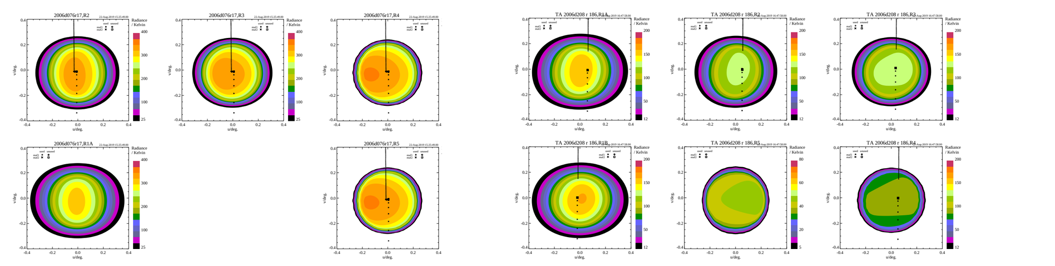
Reflector Temperature trends have continued to the present but we seek a more direct measurement of Antenna Transmission

Large and stable signal provided by the Moon can help resolve questions from long-term trending of the antenna transmission, as well as refine pointing knowledge as described above.

Moon Tracking

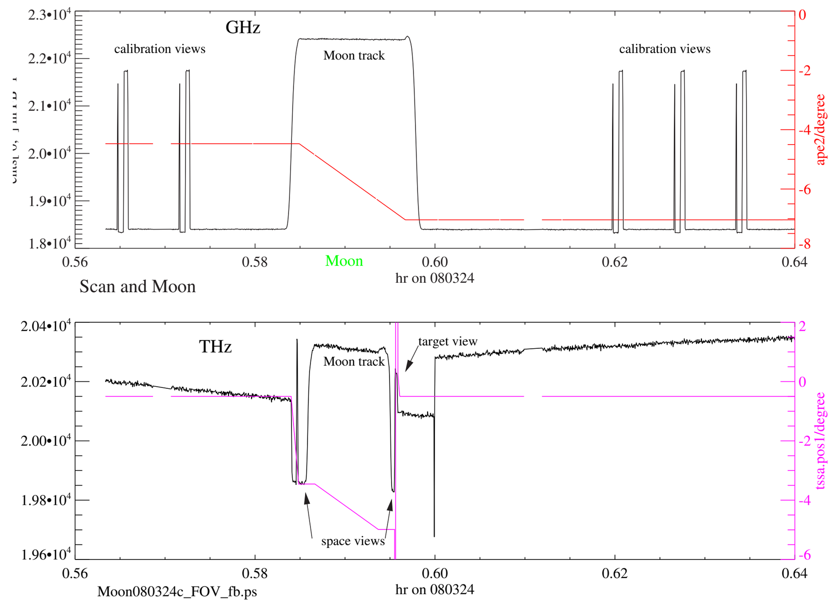
A *Moon Track*, unlike the asynchronous Moon Scan, uses a timed Master Command Load (MCL) to start a linear scan from a staring position high above the atmosphere, with velocity matching the orbital motion of the Moon, for 42 seconds (limit imposed by flight software as well as the actuator hard stop). This provides, in addition to edges, a long period of nearly constant high input radiance.

Moon tracks 2006–2019

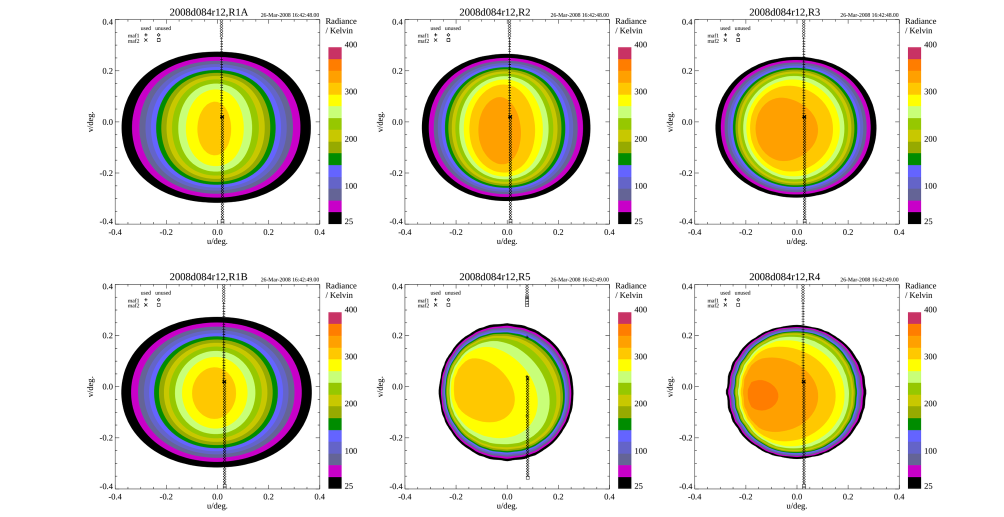


Performed above Moon tracks for both Full(L) and New(R) Moon in 2006; subsequent tracks are for Full Moon only, to maximize signal guaranteeing robust Gain retrieval. Tracks are performed at the same season, for similar $\mathbf{T_B}$ throughout years. For the same reason, Aura was slewed and held at a small Yaw angle, determined from Flight Dynamics predictions, in tracks after 2008.

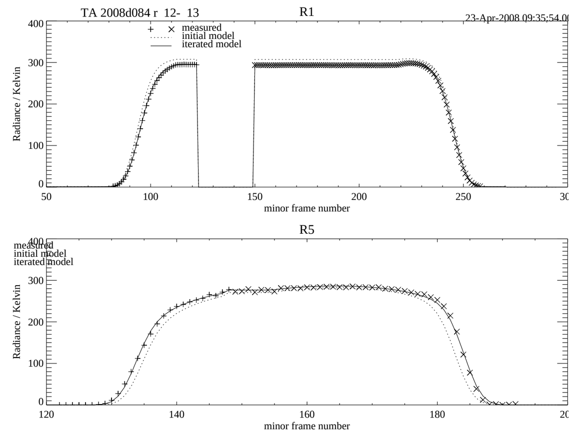
GHz and THz filter bank counts and encoder angles in a typical Moon track



Moon maps: polarized and FOV-smeared. MLS footprints extend from $\mathbf{v>0}$(before) to $\mathbf{v<0}$(after staring) connected by a segment of $\mathbf{u}$ increasing slightly due to Moon orbital motion during the 42 s stare.

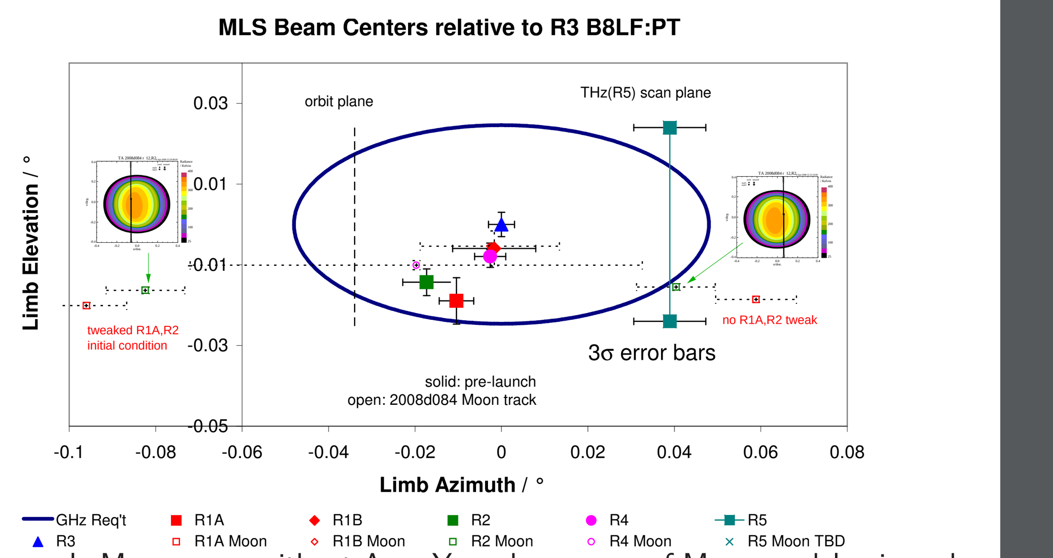


Radiance times series for 118 (top) and 2500 (bottom) GHz: measured (+) and model before(dashed) and after(solid) iteration to solve Gain and pointing angles



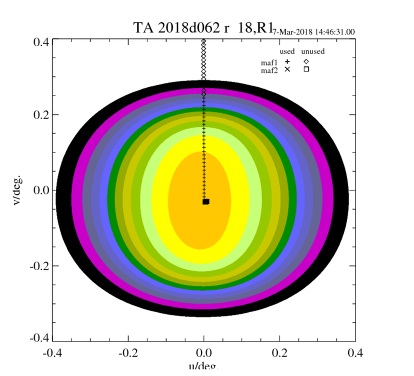
- Unfortunately, the geometry used to track the Moon suffers the same poor condition number as the Moon scans w/o yaw. The problem becomes worse the more carefully we time scans and Yaw to stare at the bright part of the Moon. Consequently the $\mathbf{A_0}, \mathbf{u}, \mathbf{v}$ retrievals must be heavily constrained to avoid coupling, especially between $\mathbf{A_0}$ and $\mathbf{u}$.
- We have recently explored alternative methods which favor the measurements over the Moon model predictions

Moon Tracks, cont.

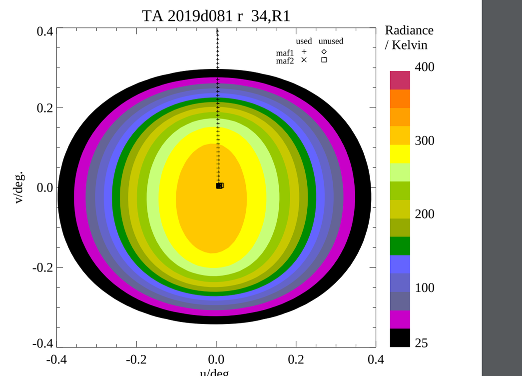


As for the early Moon scans without Aura Yaw, degeneracy of Moon model gain and horizontal pointing $\mathbf{u}$ spoils $\mathbf{u}$ retrieval (but not vertical $\mathbf{v}$); multiple solutions depend on initial condition. Pooling scans mitigates the degeneracy.

Small variations in track MCL time (e.g. 700 msec between 2018 and 2019) put the stare point at different location on the Moon; we rely on retrieved pointing to correct this effect on tracked radiance



700 msec ⇒
$\mathbf{\Delta}$ v $\sim$0.042°
$\sim$1.0 K(R1)
$\sim$1.5 K(R4)
⇒ $\mathbf{\Delta}$ $\mathbf{(A_0)}$
$\sim$ 0.0046



Antenna Transmission Trends

GHz radiometer	R1A	R2	R3	R4	R1B
$\mathbf{A_0}$ "Gain"	0.986	0.947	0.917	0.927	0.929
σ 1day	0.001	0.0017	0.0019	0.0040	0.0010
σ pooled	0.025	0.054	0.017	0.031	0.009
$\mathbf{\Delta A_0}$ trend over 2010–2019	+0.002*	-0.005	+0.025*	-0.005	+0.020*

* are not significant due to retrieval issues

- No Gain change can be inferred for R1A,R3 and R1B
- A statistically significant Gain change for R2 and R4, each -0.005 over the period [2006,2019], may be due to degradation of the VDA surface of the Primary Reflector; needs more validation before offering to flight processing software.

Conclusions

- The current program of $\sim$annual scan program changes, synchronized with spacecraft Yaw maneuvers, has provided valuable insight into antenna pointing and transmission, with minimal impact to the science observation time of Aura MLS.
  - Pointing determined through 2004-2008 and 2010 scans has been confirmed at values measured in pre-launch pattern measurements
  - Yearly Moon Tracks since 2006 (2 yr after launch) have provided bounds on long-term change in Antenna Transmission which vary from 0 to -0.005 over the 5 GHz radiometers. No significant changes have been detected to the level of Level 2 and forward-model sensitivity.
  - We will continue performing yearly Moon Tracks through end-of-life, as allowed by the Aura decommission plans, and enhancing the transmission/pointing retrieval methods.